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FINAL REPORT

on

DEVELOPMENT OF A FLUID CONCENTRATED DISPERSION OF A WATER-SOLUBLE POLYMER CAPABLE OF REDUCING THE FRICTION OF WATER UNDER TURBULENT CONDITIONS

to

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Washington, D. C. 20007

Contract No. Nonr 4827 (00)

by

R. H. Forester
L. T. Rozelle
R. E. Larson

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NORTH STAR RESEARCH AND DEVELOPMENT INSTITUTE
[illegible] 38th Avenue South, Minneapolis, Minnesota [illegible]
[illegible]

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TABLE OF CONTENTS

ABSTRACT

Dispersions (slurries) of up to 45 weight percent water-soluble polymers in nonsolvent carriers were effective for reducing drag in turbulent flowing water streams. Separan or Polyox, in polypropylene glycol, gave about 20 percent friction reduction in mixing times less than 0.3 seconds, and reductions of over 60 percent in 1.5 seconds, in a 0.26-inch i.d. tube. In a 10-inch pipe, friction reductions of 30 percent were obtained. Decreasing the water temperature from 40°F to 30°F, and adding 3.5 percent salt to the water had only minor effects on friction reduction. The optimum concentration of polymer in the water stream was approximately 80 ppm. Dispersions of polymer have been held 18 months without settling or dissolving.

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SUMMARY

In the first phase of the current research program for the Naval Ship Research and Development Center, from June 15, 1965, to July 31, 1966, North Star Research and Development Institute investigated the feasibility of using water-soluble polymers to reduce the friction caused by turbulent flow of water.(1)* By employing concentrated dispersions (slurries) of polymer in nonsolvent carriers, which were, in turn, soluble in water, friction reduction could be obtained almost immediately on injection into a test stream. Prototype 10-percent slurries of various drag-reducing polymers were injected into flowing turbulent water streams, and friction reductions as great as 50 percent were noted in mixing times as short as 1.5 seconds. Greater friction reduction was achieved at somewhat longer times.

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*Superscripts refer to literature references at the end of the report.

This report summarizes results of the ..cond phase of this study -- from August 1, 1966 to January 31, 1·08. The overall objective was to continue development and optimization of a concentrated fluid system which contains more than 10 percent, by weight, of a ..·ion-reducing water-soluble polymer. This program included detailed consideration of the following tasks:

- Determination of maximum concentration of drag-reducing polymer that can be incorporate· in the dispersion and still be effective on injectio· into water streams.
- Development of dispersions with long-term stability.
- Formation of useful and stable dispersions from a wider number of drag-reducing polymers.
- Determination of the effects of polymer particle size.
- Characterization of the effects of water temperature and salinity on polymer hydration rates.
- Determination of the minimum amounts of slurry that can be injected into water and still achieve necessary drag reduction.

The major effort of the initial part of the current program was directed toward the development of a means for preparing stable slurries containing high concentrations of water-soluble polymers that are capable of friction reduction. Slurries containing 50 percent polymer were obtained using simple dispersion equipment. Successful completion of this phase of the study led to the second phase, in which the slurries were evaluated. A water-flow facility and a slurry injection system were designed and built. Three polymers were selected for testing from those found effective in the earlier studies.

Because of system flow limitations and injection-system pressure requirements, the measurements in the North Star water-flow

facility were limited to the use of low-solids slurries (less than one percent). High-solids slurries (45 percent) were tested in a ten-inch diameter water-flow system at the Saint Anthony Falls Hydraulic Laboratory of the University of Minnesota. The North Star slurry injection system was used for both studies.

The results of the program are summarized as follows:

1. Slurries of water-soluble polymers in polypropylene glycol are practical for reducing friction in turbulent flow. The preparation of the slurries is simple, the slurries are stable in long-term storage, are easily pumped, and the injection apparatus and nozzles are unsophisticated and reliable.
2. Anhydrous polypropylene glycol with a molecular weight of about 400 was found to be a suitable water-miscible, nonsolvent carrier. A silica aerogel (less than one percent) was satisfactory as an antisettling agent. One sample of a 35-percent slurry has shown no settling, and the polymer has shown no tendency to dissolve in over 18 months of storage.
3. When 80 ppm of Separan or Polyox were injected into the water flow in the North Star facility, friction reductions as large as 65 percent were obtained at Reynolds numbers from 3×10^4 to 5.4×10^4.
4. Friction reductions of 30 percent were measured in the University of Minnesota's ten-inch facility at Reynolds numbers from 2.6×10^5 to 7×10^5.
5. The friction reduction effects were increased by utilizing polymer particles of smaller size and increasing the mixing time between injection of the polymer slurry into the water and measurement of the friction reduction.
6. Decreasing the water temperature from 40 F to 30°F, using a 3.5-percent NaCl-water solution instead of tap

water, and reducing the Reynolds number in the test section of the water-flow channel below 30,000 had only minor effects on friction reduction.

7. Increasing the polymer concentration above 80 ppm and increasing the water temperature from $40^{o}F$ to $80^{o}F$ had no effect on friction reduction.

INTRODUCTION

In recent years, considerable interest has been shown in the phenomenon of drag reduction in water under turbulent flow conditions caused by the addition of certain water-soluble polymers.[2,5] Drag-reducing polymers offer the U. S. Navy a potential for reducing the drag of ship and torpedo hulls, and also promise to reduce turbulent noise around sonar domes.[6,7] Work has progressed to a point where the Navy is beginning to consider methods of applying these polymers to actual ships. Several methods exist, but they are not entirely suitable.

Concentrated stock solutions of drag-reducing polymers have been considered in the past.[8,9] However, the polymers generally have high molecular weights and, when dissolved at concentrations in excess of one percent, form extremely viscous, almost gelatinous solutions. Such solutions would be hard to handle and disperse. If they were carried on board ship in concentrations that would allow them to be pumped (less than one percent), their storage would require a large volume and add considerable weight to the ship.

There has been some success with mixing dry polymers into fast-moving streams of water, especially in the petroleum industry.[10] This process could conceivably be utilized by the Navy; however, such methods invariably include air in the mixture and could cause

difficulty in applying drag-reducing agents to sonar domes. Bubbles would be expected to cause additional noise, which would, in effect, reduce the sensitivity of the sonar.

The concentrated-slurry approach was suggested by North Star as one of the most promising methods of adding drag-reducing polymers to water [13]. Studies at North Star have been directed toward the development of concentrated fluid dispersions of drag-reducing polymers in water-miscible liquids that suspend, but do not dissolve, the polymers. Because the polymer is not dissolved, high concentrations can be obtained without intolerably high viscosities. The polymer remains suspended in the liquid as discrete particles until such time as the slurry is injected into, and mixed with, water. The polymer then hydrates rapidly, so that it can effect almost immediate drag reduction. This approach permits the use of high concentrations of polymer particles in a slurry that can be readily pumped and injected into the water. Dispersion techniques are simple, and the storage bulk of the slurries is reduced considerably.

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

North Star Water-Flow Test Facility

The North Star water-flow test facility consists of a reservoir, a turbine-type pump, a two-inch diameter mixing section, and a 0.265-inch ID test section, 10 feet long. A sketch of the system is shown in Figure 1. A test-section bypass system was installed so that slurries could be injected under identical flow conditions, although the flow in the test section was varied. The flow was measured with an orifice flow meter at the pump outlet and with a rotameter in the bypass system. The maximum Reynolds number for the test section was 100,000; the Reynolds number of the mixing section was maintained at 25,000. The mixing time for the polymer slurry was varied by injection of the slurry through one of five injection ports installed in the mixing section.

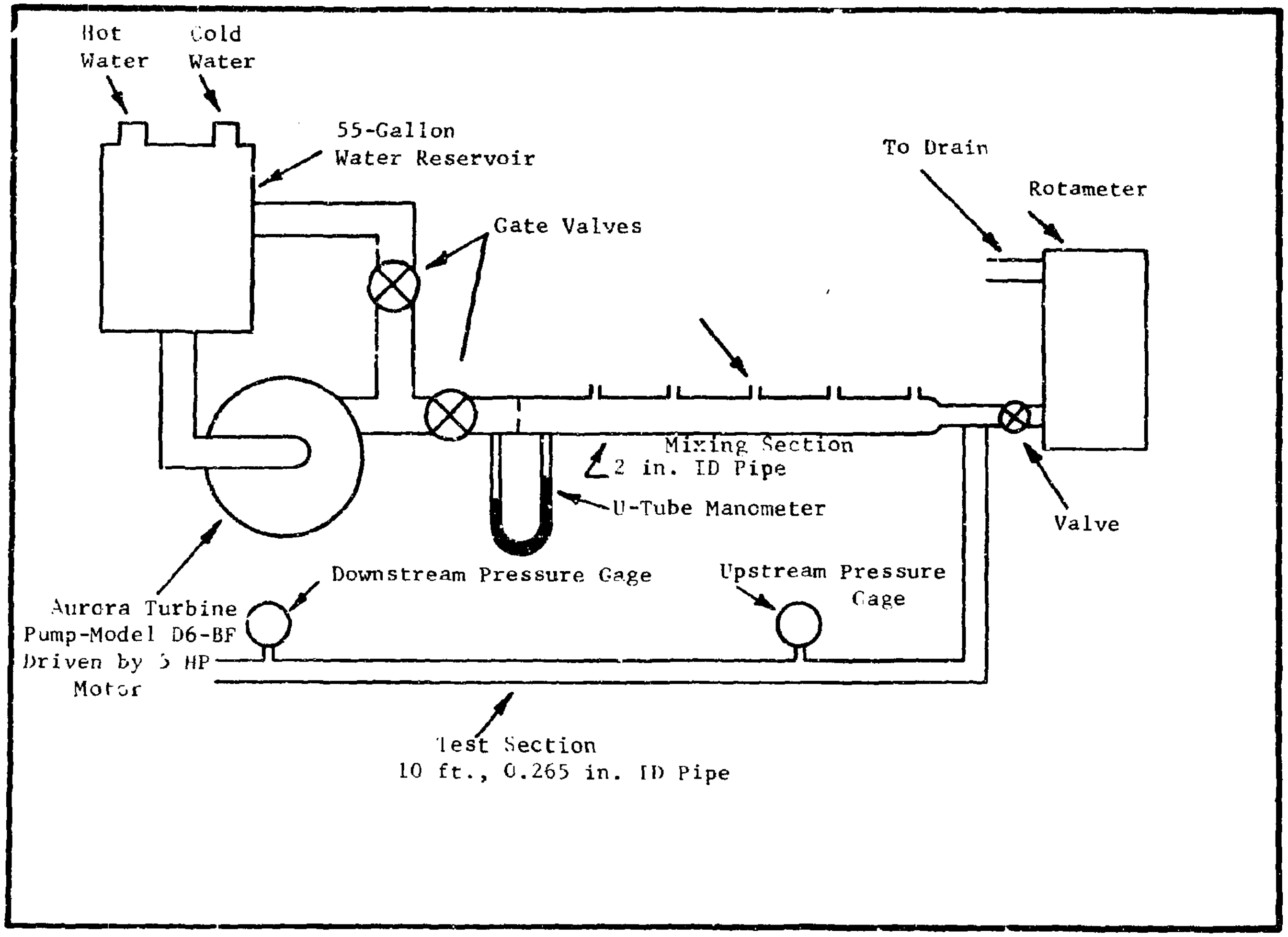

FIGURE 1. WATER FLOW TEST FACILITY

University of Minnesota Water-Flow Test Facility

In addition to the North Star test device, the 10-inch diameter flow facility at the St. Anthony Falls Hydraulic Laboratory (SAFHL) of the University of Minnesota was utilized. A sketch of this facility is shown in Figure 2. It draws water from the Mississippi River above St. Anthony Falls and has about a 30-foot drop to the river below the Falls. An auxiliary pump, which can generate approximately 20 feet of head, combined with the drop to the river, can provide a test-section velocity of 15 feet per second (8.4 cubic feet per second). A control system allows variation of the velocity from zero to the maximum value. The test section is equipped with Plexiglas viewing sections. A flow straightener is located at the inlet of the horizontal section of the pipe. The polymer slurry injection system was installed downstream of the straightener. The injection nozzle was positioned in the center of the 10-inch pipe, pointing downstream. A downstream view of the test section is shown by photograph in Figure 3. Some of the associated equipment shown in the photograph is related to other SAFHL projects using the facility.

Polymer Slurry Injection System

This sytem was built around a screw-type pump suitable for handling high-solids slurries. The injection system and the pump are shown in Figures 4 and 5. The pump output was controlled by a variable-speed drive system, and an orifice-type flow meter was used to measure the flow. The system was also equipped with a small-diameter nozzle bypass channel, through which the flow could be directed while the injection rates were established. In use, the flow in the injection system was adjusted using the bypass channel,

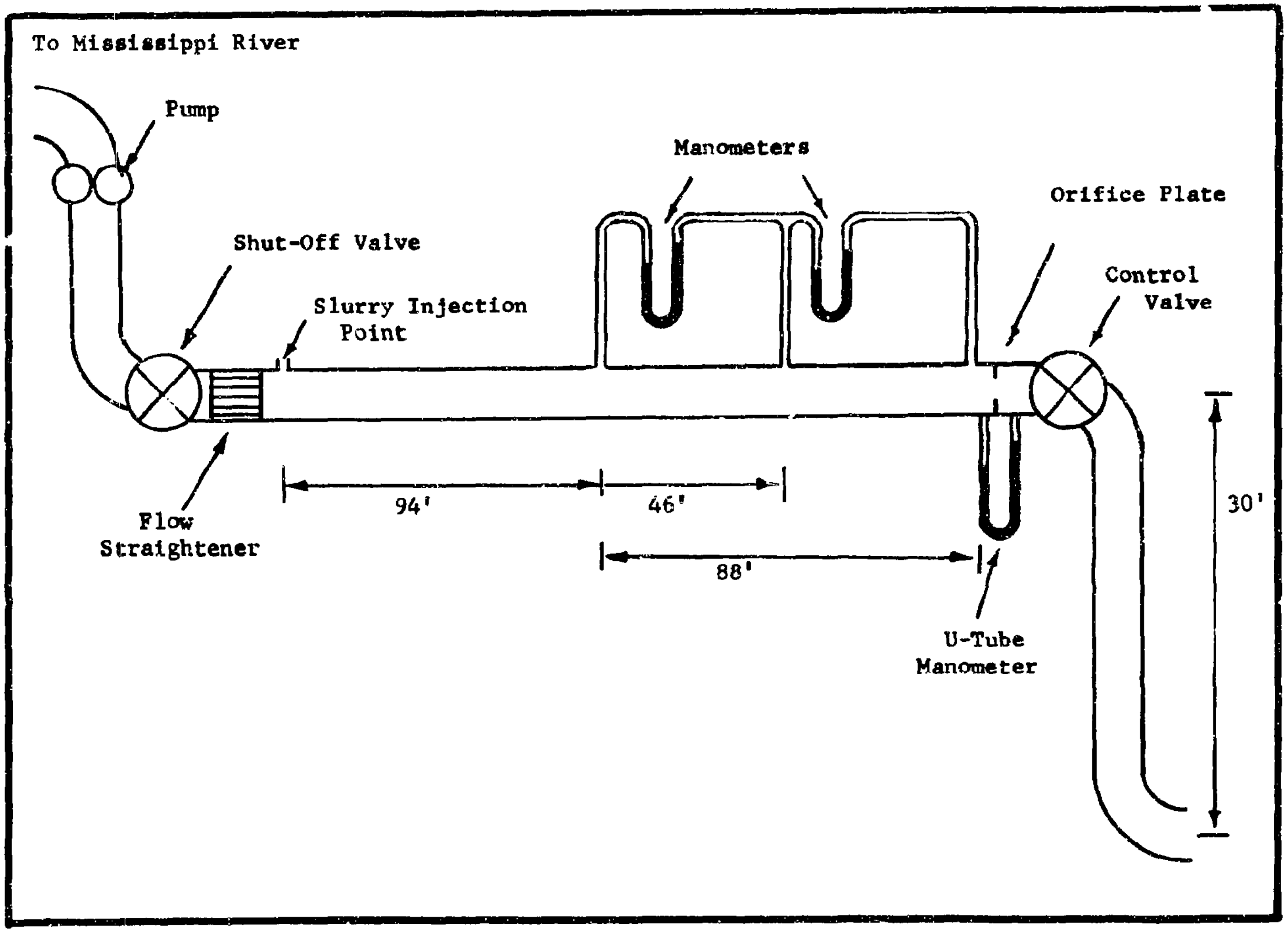

FIGURE 2. SKETCH OF 10-INCH DIAMETER FLOW SYSTEM AT ST. ANTHONY FALLS HYDRAULIC LABORATORY

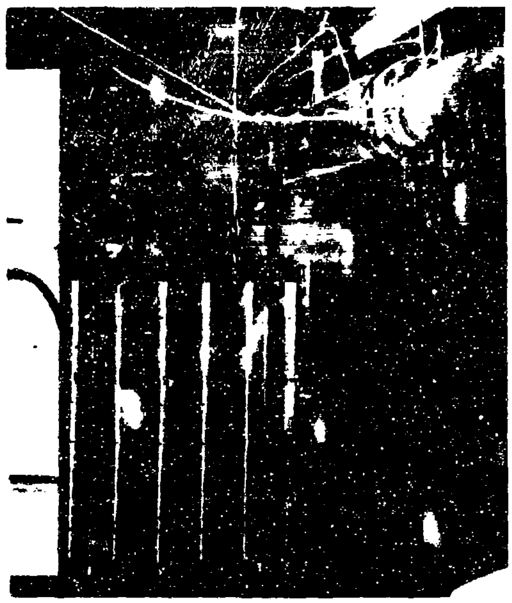

FIGURE 3. PHOTOGRAPH OF SAFHL 10-INCH FACILITY SHOWING TEST SECTION OF PIPE

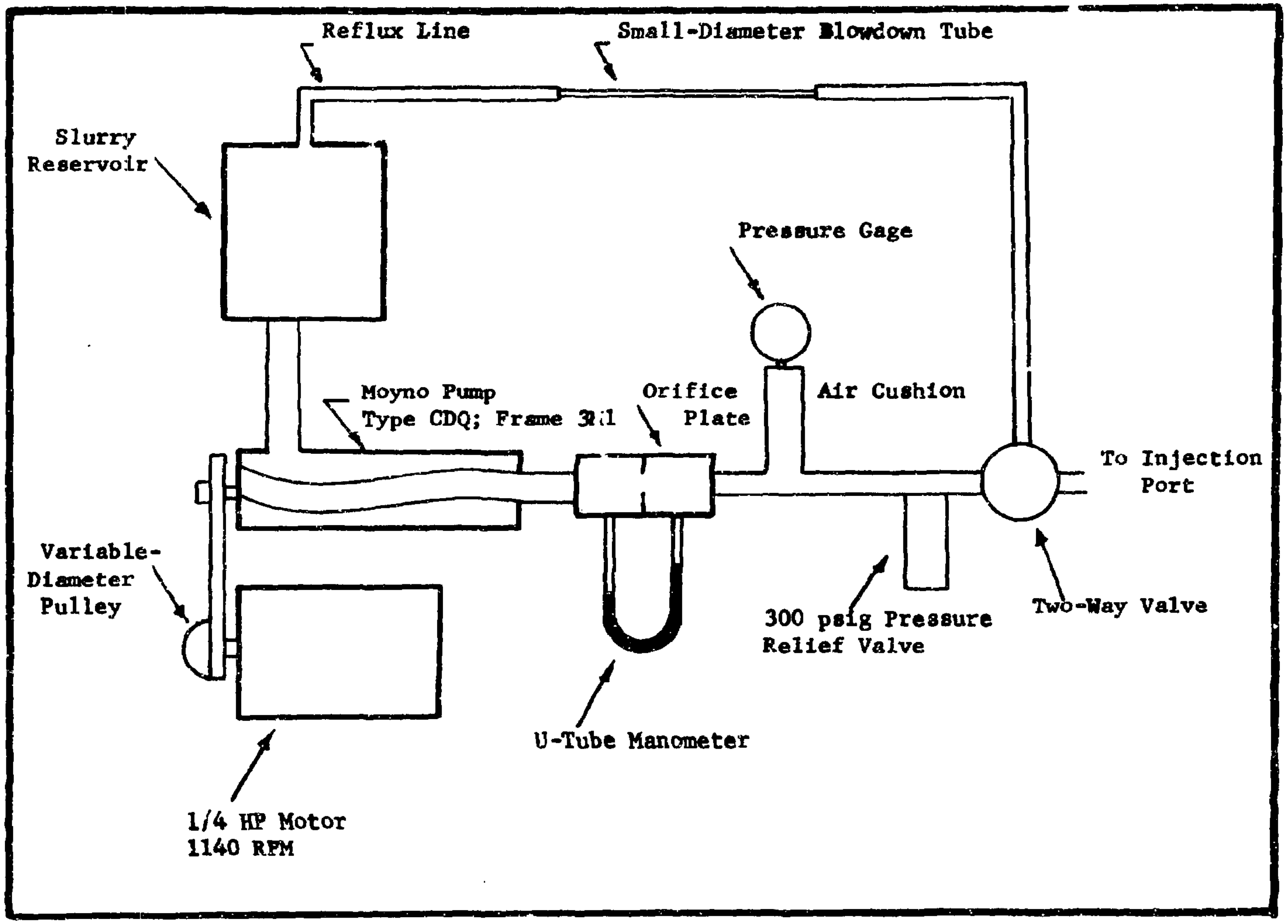

FIGURE 4. POLYMER SLURRY INJECTION SYSTEM

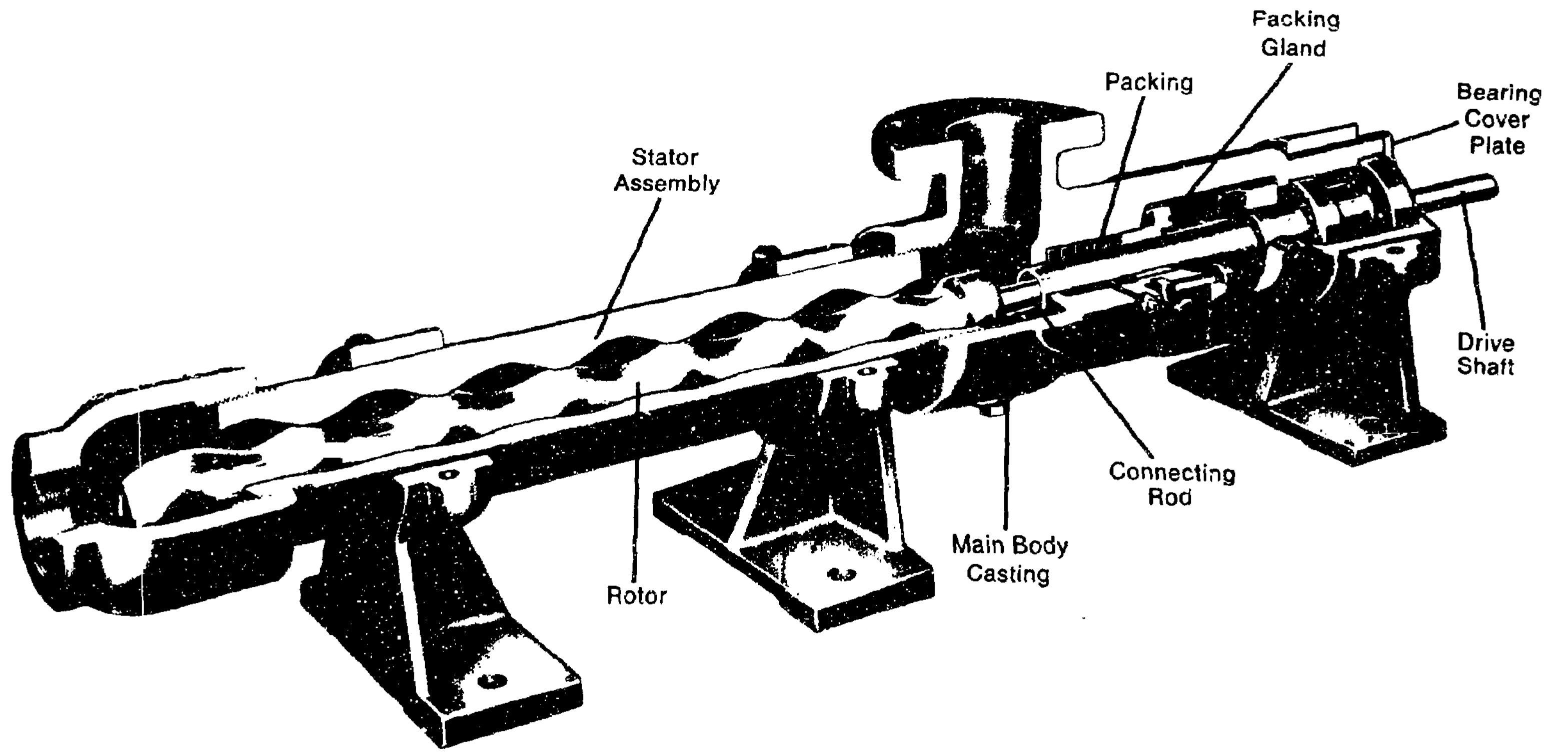

FIGURE 5. DIAGRAM OF SLURRY INJECTION SYSTEM PUMP

which had a pressure drop that equaled the nozzle pressure loss, and little, if any, adjustment was required after the slurry flow was switched to the test channel through a two-way valve.

The injection system worked properly only when slurries containing 10 percent or less water-soluble polymer (WSP) were used. When the slurry concentration was increased to 35 to 50 percent WSP, the pump could not supply adequate pressure to handle the slurry. The high pressure drop was caused by small orifices in the orifice-type flow meter and control valves. An improved injection system is shown in Figure 6. This device included a second reservoir to allow the system to be flushed with the carrier liquid between tests, which prevented water from mixing with the high-solids slurry through the nozzle. Such contamination, with a concentrated slurry, can result in a viscous plug in the outlet, blocking the nozzle. These plugs were not viscous enough to block even small orifices when the slurry concentration was 10 percent or less.

The injection system was calibrated by setting the variable-speed pully and discharging the slurry through the injection nozzle into a container on a weighing scale. The pump is nearly a constant-volume type, and since the system was used in a low-pressure water channel, the pump output was assumed to be the same as when calibrated.

The studies indicated that high polymer concentration can be attained in the slurry and that compact injection devices can adequately handle the slurry. Therefore, large quantities of water can be treated readily. The injection system described was mounted on a platform about two-feet square and was capable of treating 2:00 GPM of water adding 80 ppm of polymer.

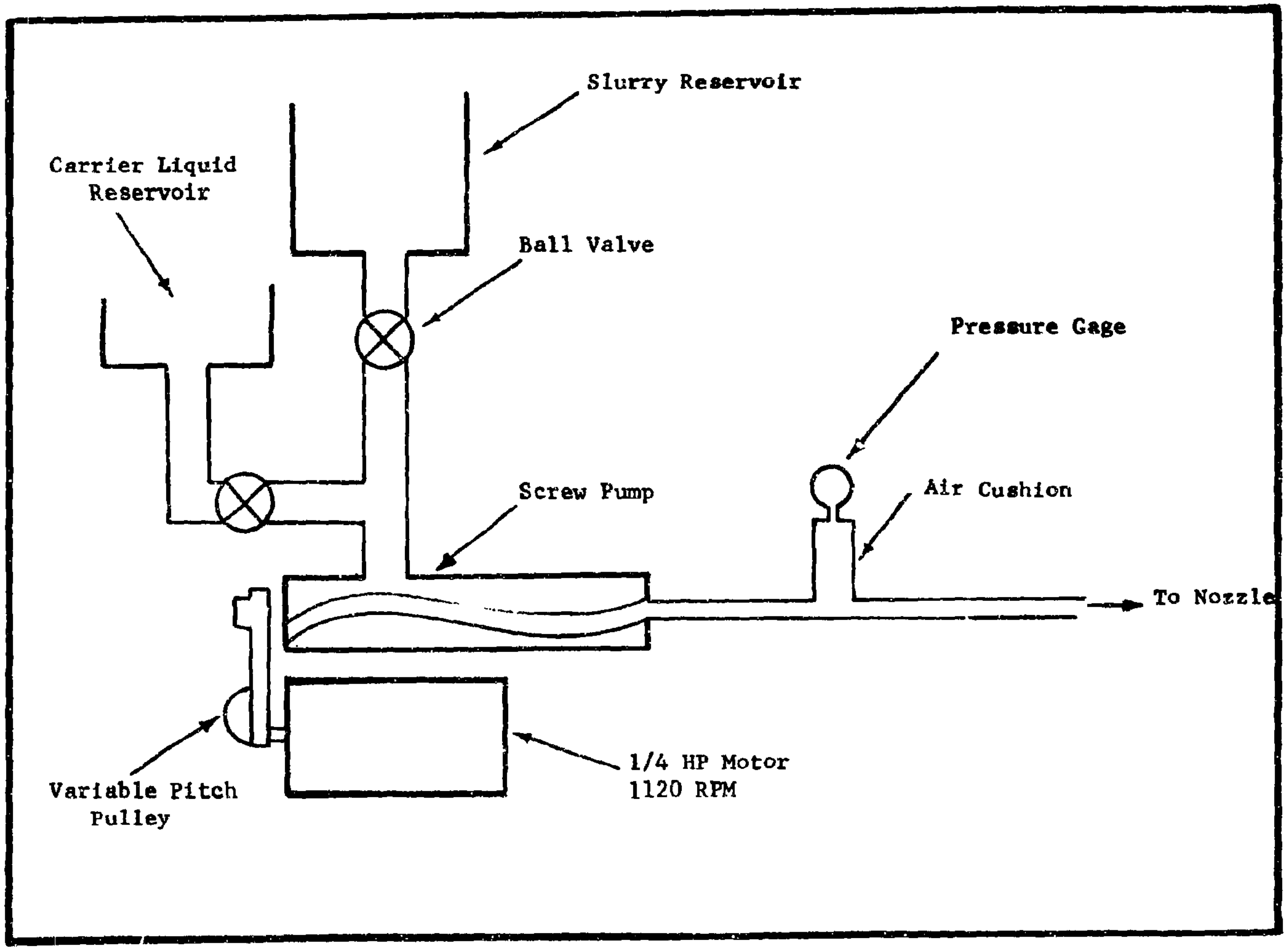

FIGURE 6. SLURRY INJECTION SYSTEM MODIFIED FOR USE WITH HIGH-SOLIDS SLURRIES

Test Procedure

The procedure followed for most of the tests was to compare the pressure drops in the test section at a given flow rate for water alone with the pressure drops for water with polymer supplied by the injection system. The results are presented as percent friction reduction, calculated from

$$\text{Percent reduction} = \left(\frac{\Delta p_1 - \Delta p_2}{\Delta p_1}\right) \times 100$$

where: Δp_1 = pressure drop for water alone

Δp_2 = pressure drop for water plus polymer

To explore environmental effects, experiments were run in which the water temperature and salinity of the system were varied.

A slightly different procedure was followed when the 10-inch diameter facility at SAFHL was used. The injection system was calibrated by running slurry into a beaker on a weighing scale. The system was flushed with polypropylene glycol (PPG) before and after each test.

TEST RESULTS

Injection Nozzle Selection

The method of injecting the polymer slurry into the water is very important in the friction reduction studies. Injection flow characteristics for various nozzles were determined by visual observation of flow in a two-inch diameter Plexiglas tube. Flow in the tube was maintained at a Reynolds number of about 5000, well under that of the mixing section of the North Star water-flow facility.

This assured that mixing of polymer slurry in the friction-reduction test facility would be at least as good as that observed in the Plexiglas tube.

For the flow visualization studies, a water-soluble red dye was added to the slurries. The dispersion pattern was thus visible, and any tendency for the slurry to settle or to stick to the tube wall could be seen readily.

Figure 7 shows a satisfactory injection pattern, using a Vee Jet nozzle supplied by Spraying Systems, Inc. Figure 8 shows an example of an unsatisfactory pattern. The satisfactory nozzles were designed to spray a narrow, flat pattern of liquid into air. They operate at pressures from 20 to 400 psi, and are available in sizes ranging from 0.15 to 300 gpm. A pressure drop of about 40 psi across the nozzle was necessary to obtain a satisfactory dispersion pattern when spraying the slurries into water. Also, the orifices in the nozzle must be significantly larger than the particles in the slurry to avoid plugging.

The required nozzle orifice size and pressure drop for satisfactory polymer injection established the minimum flow of slurry that could be used in the test system. It was about 700 grams per minute. The water flow in the North Star test facility was about 30 kilograms per minute when the Reynolds number of the test section was about 100,000. During most of the studies, polymer concentrations of the order of 100 ppm were added to the water. The concentration of polymer in the slurry, therefore, had to be very low to avoid an excessive polymer addition. Less than one percent polymer in the slurry was used for the tests at North Star. In the studies carried out in the 10-inch diameter test facility at SAFHL, high-solids slurries of 45-percent concentration were used.

FIGURE 7. SATISFACTORY HIGH SOLIDS SLURRY INJECTION
SLURRY STAINED WITH RED DYE FOR OBSERVATION

WATER FLOW ~ 30 GPM

FIGURE 8. POOR INJECTION PATTERN
USING DYED POLYMER SLURRY

Polymer and Nonsolvent Carrier Selection

Several linear, high molecular weight, water-soluble polymers are commercially available. From the materials available, three were selected. Included were an anionic type (a polyacrylamide, Separan AP30, Dow Chemical Co.), a nonionic type (polyethylene oxide, Polyox Coagulant, Union Carbide Corp.), a cationic type (Reten 210, Hercules Corp.). Another polyacrylamide, Polyhall 27 (Stein Hall and Co.), was also tested in this program because it gave good friction-reduction results in the previous program.

Table 1 shows the friction reduction of the three polymers at various concentrations in the test water. Polyox and Separan gave comparable results, and Reten was less effective. The optimum concentration for friction reduction is about 80 ppm for all the polymers tested; higher concentrations contributed little.

Polyhall 27 gave a friction reduction considerably lower than the other polymers and was omitted from the balance of the program.

The criteria for the nonsolvent carrier were as follows:

1. It should be a nonsolvent for the polymer.
2. It should be miscible with water.
3. It should have a low viscosity.
4. It should be anhydrous.
5. For practical use, it should be reasonably priced, non-corrosive and have a high flash point.

All these criteria were met by a urethane grade polypropylene glycol (PPG), which has a molecular weight (MW) of approximately 400. The properties of this material are listed in Table 2.

TABLE 1

EFFECT OF POLYMER CONCENTRATION IN WATER ON FRICTION REDUCTION IN NORTH STAR TEST FACILITY

Mixing Time = 6.1 Seconds
Temperature = 45°F
N_{Re}, Test Section ~ 6.4×10^4
Velocity Test Section = 45 fps

Polymer	Concentration In Water, PPM	Friction Reduction, %
Polyox, Coagulant	160	65
	80	62
	40	57
	20	38
Reten 210	200	56
	160	56
	80	50
	40	43
Separan AP30	200	66
	160	66
	80	66
	40	59
	20	45
Polyhall 27	160	45

TABLE 2

PHYSICAL PROPERTIES OF
400 MW POLYPROPYLENE GLYCOL, URETHANE GRADE

Specific Gravity, 20/20°C	1.01
Pour Point	-49°F
Flash Point	390°F
Fire Point	405°F
Viscosity, 77°F	70 Centipoise
Vapor Pressure	0.01 mm Hg at 68°F
Water Content	<0.05%

Data Sources: Dow Chemical Company
Union Carbide Corporation

Polymer Slurry Preparation

Investigation of slurry preparation consisted of four phases; determining maximum practical slurry concentration, development of the method of dispersing the polymer in the nonsolvent, stabilization of the slurry against the particles settling or dissolving, and observations of long-term stability.

The polymers used were commercial products, having wide variations in particle size. The particles were classified into size ranges between 63 to 125 microns by passing the particles through standard sieves and collecting the fractions. Particles in this range are generally considered easy to disperse; this was found to be true in our studies. The fractions were stored in polyethylene bags to prevent contamination.

Two methods of dispersing the polymer particles in the nonsolvents were investigated. For the first, polymer was dispersed by high-shear mixing in a Waring Blendor; and in the second, a pebble mill was used. These methods were selected because similar equipment is available in production sizes. However, the pebble mill provided results superior to these obtained with the Blendor, and it was used for preparing most of the dispersions. A laboratory-

size pebble mill dispersed efficiently a mixture of 50-percent polymer in carrier in about five hours. The degree of dispersion was determined by examining the slurry under a low-power microscope. From such observation it was apparent the particles were discrete.

The stability of the slurries was studied following two criteria. The first was noting whether the polymer particles tended to be dissolved by the PPG carrier. Samples of three polymer dispersions (Separan AP30, Polyox Coagulant, and Reten 210) were observed for six months, and no signs of dissolving were observed. The particles remained discrete, grainy, and showed no signs of stickiness that would have indicated partial solution.

The second criterion of slurry stability was an observation of the settling of the polymer particles in the slurry. Because the particles were relatively large and well dispersed, the slurries settled rapidly, and in a few days a firm precipitate resulted. This precipitate could be stirred-up quite easily, however. The settling was controlled by adding a silica aerogel pigment (Cab-O-Sil, M5, Cabot Corp.) to the slurry. This was most effectively done using a high-shear mixer, such as the Waring Blendor.

A 30-percent slurry of Polyox Coagulant in 400 MW PPG was observed for 18 months. This slurry was prepared in a Blendor and contained about 2½ percent Cab-O-Sil. There was essentially no change in this slurry during the 18-month period. No noticeable settling had occurred, and the Polyox particles remained hard and grainy; an indication that they were not dissolving.

Fifty-percent polymer slurries can be pumped with the screw-type pump used on this program. The slurries are thixotropic, which reduces the pumping energy needed, while reducing the tendency to settle in storage. Figure 9 shows the effect of shear rate on

viscosity for a 50-percent Separan slurry containing 0.8 percent Cab-O-Sil. The measurements were made with a Brookfield Viscometer (Model LVT). The abscissa is marked in centimeters per second, which is directly proportional to the shear rate. The plot is typical of thixotropic materials.

Mixing Time

The North Star water-flow system has a mixing section with five ports for injection of the WSP slurry. Each of these ports provides a different mixing time for the WSP with water before the water enters the test section. Table 3 shows the effect of mixing time on friction reduction for mixing times of 6.10, 3.10, and 0.26 seconds.

TABLE 3

EFFECT OF MIXING TIME ON FRICTION REDUCTION
IN NORTH STAR TEST FACILITY

Polymer	Concentration In Water, PPM	Mixing Time, Seconds	Friction Reduction, Percent
Polyox	100	6.1	65
		3.1	50
		0.26	19
Separan	80	6.1	66
		3.1	54
		0.26	21
Reten	100	6.1	56
		3.1	40
		0.26	2

Particle Size, 125-250 Microns
Water Temperature ~ 45°F
N_{Re} Test Section ~ 64,000
Velocity Test Section 45 fps

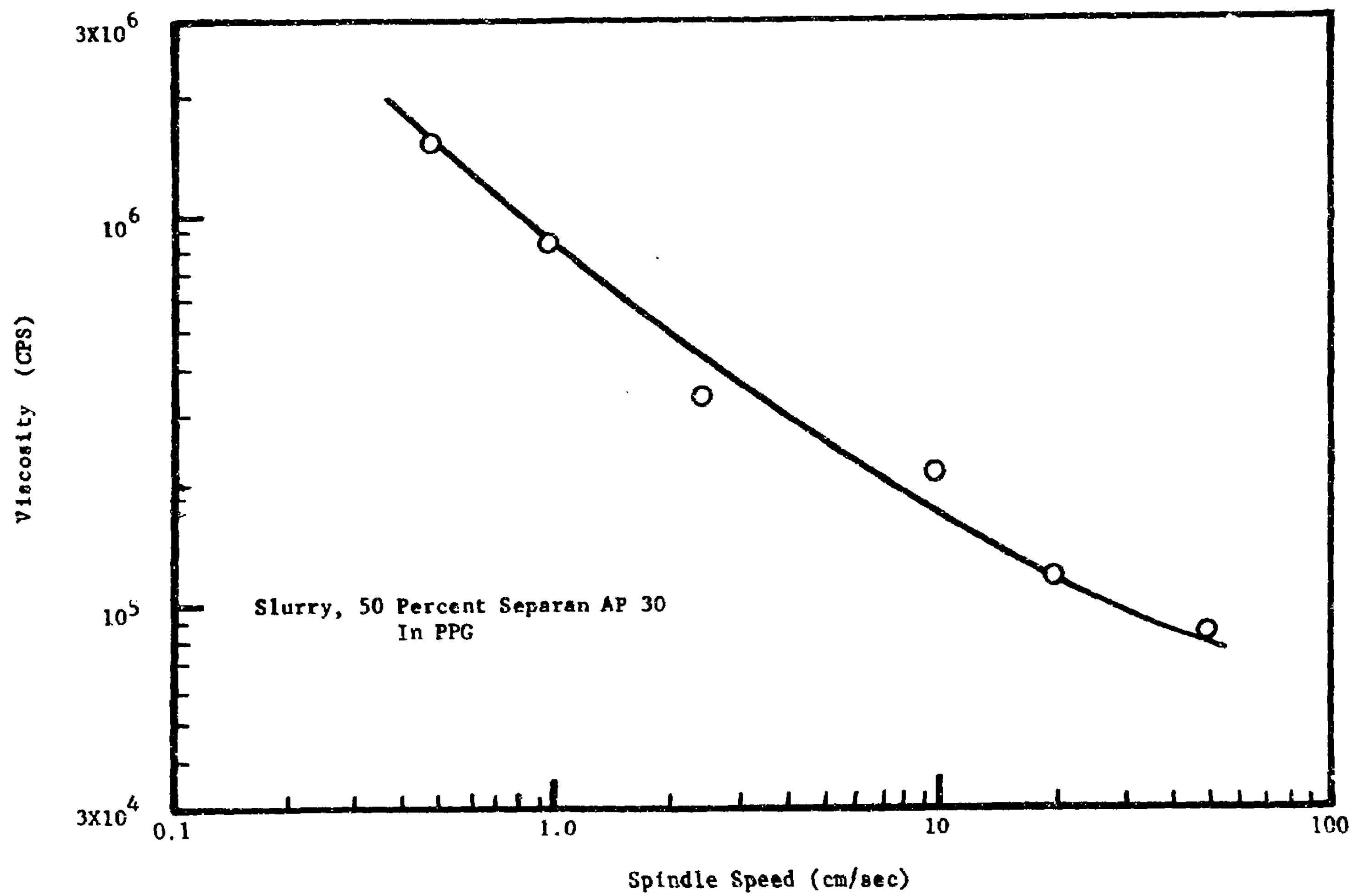

FIGURE 9. RELATIONSHIP BETWEEN VISCOSITY AND SHEAR RATE (SPINDLE SPEED)

Separan and Polyox dissolve faster than Reten; both the former show about 20-percent friction reduction in 0.26 seconds, while the latter shows very little. In 3.1 seconds, the two best polymers gave at least 50-percent friction reduction.

The WSP's used in this project were granular materials that had a wide range of particle sizes. To test the effects of particle size, the WSP's were sieved into various classifications before being dispersed in the carrier liquid. Table 4 shows the effect of particle size on friction reduction for Polyox and Separan. The results indicate very little difference between the two polymers. For mixing times longer than 3.1 seconds, the particle-size effect disappeared.

One attempt was made to reduce the particle size by grinding dry polymer in a pebble mill. It was possible to reduce the particle size this way, but the process was too slow for practical use. It is probable, however, that commercial equipment could be used for size reduction. It appears that, if polymer particles were a few microns in size, the friction reduction would take place more rapidly. The decrease in particle size would result in longer time required to disperse the polymer in the nonsolvent carrier, and could limit the polymer content of the slurry. Since 50 percent does not appear to be the maximum polymer content that could be obtained with commercial dispersing equipment, this concentration could be maintained even if the particle size were greatly reduced. Smaller polymer particles would also aid in preventing settling in stored slurry. The nozzle-plugging problem that occurred in this program probably could have been avoided if fine-particle slurries had been available. The polymer injection nozzles used had orifices only a few times larger than the particle diameter and were subject to occasional partial plugging from foreign material. When 50-percent slurries were used (of particles finer than 120 mesh), a partial plug

TABLE 4

EFFECT OF PARTICLE SIZE ON FRICTION REDUCTION IN NORTH STAR TEST FACILITY

Water Soluble Polymer and Concentration	Particle Size, Microns	Mixing Time, Seconds	Friction Reduction, Percent
Polyox 100 ppm	125-250	0.26	19
	< 125	0.26	29
	125-250	3.1	50
	< 125	3.1	60
Separan 80 ppm	125-250	0.26	21
	< 63	0.26	30
	125-250	3.1	54
	< 63	3.1	60
Polyox 60 ppm	125-250	0.26	39
	125-250	3.1	63
	125-250	5.9	64
	125-250	8.7	67
	125-250	11.2	67

Water Temperature ~ $50^{\circ}F$
N_{Re} Test Section ~ 70,000
Velocity, Test Section ~ 45fps

in the nozzle left a thick mass of polymer granules when the non-solvent carrier drained away. Finer polymer particles would not have caused plugging.

During the tests in the 10-inch facility, a stream of un-dissolved polymer particles could be seen flowing through the Plexiglas viewing sections. Finer particles would dissolve more completely and would increase the efficiency of the injection system. In all probability, concentrations of polymer lower than 60 to 80 ppm in water would then be the optimum for friction reduction.

Temperature and Salinity Effects

Most of the friction reduction studies were performed using tap water at temperatures from 40°F to 50°F. Tests run with 80°F water showed no change in friction reduction; in salt water (3.5 percent NaCl in tap water), friction was reduced slightly less; cold salt water (30°F) further decreased the friction-reduction effect. The results of these experiments are shown in Table 5. The combined effects of salt and cold water, however, were not great.

Effect of Reynolds Number Variation on Friction Reduction

Previous studies on friction reduction in pipe flow reported a decrease in friction reduction as the Reynolds number is lowered.[12,13,14] This effect was also investigated in this program. Figure 10 shows the effect of Reynolds number on friction reduction. A Reynolds number of 20,000 was the lowest value used in the North Star facility. This was because of limitations in the system instrumentation.

TABLE 5

EFFECTS OF SALINITY AND TEMPERATURE ON FRICTION REDUCTION

Polymer Type	Water Soluble Polymer Concentration, ppm	Water Temperature, °F	NaCl Concentration, Percent	Friction Reduction, Percent	N_{Re} Test Section
Separan AP30	80	45	0	66	64,000
	160	40	3.5	64	60,000
	160	30	3.5	59	50,000
	80	30	3.5	63	50,000
Polyox Coagulant	160	40	0	65	60,000
	160	40	3.5	61	60,000
	160	30	3.5	57	50,000
Reten 210	160	40	0	56	60,000
	160	30	3.5	56	30,000
	160	30	3.5	51	30,000

Velocity In Test Section = 45 fps

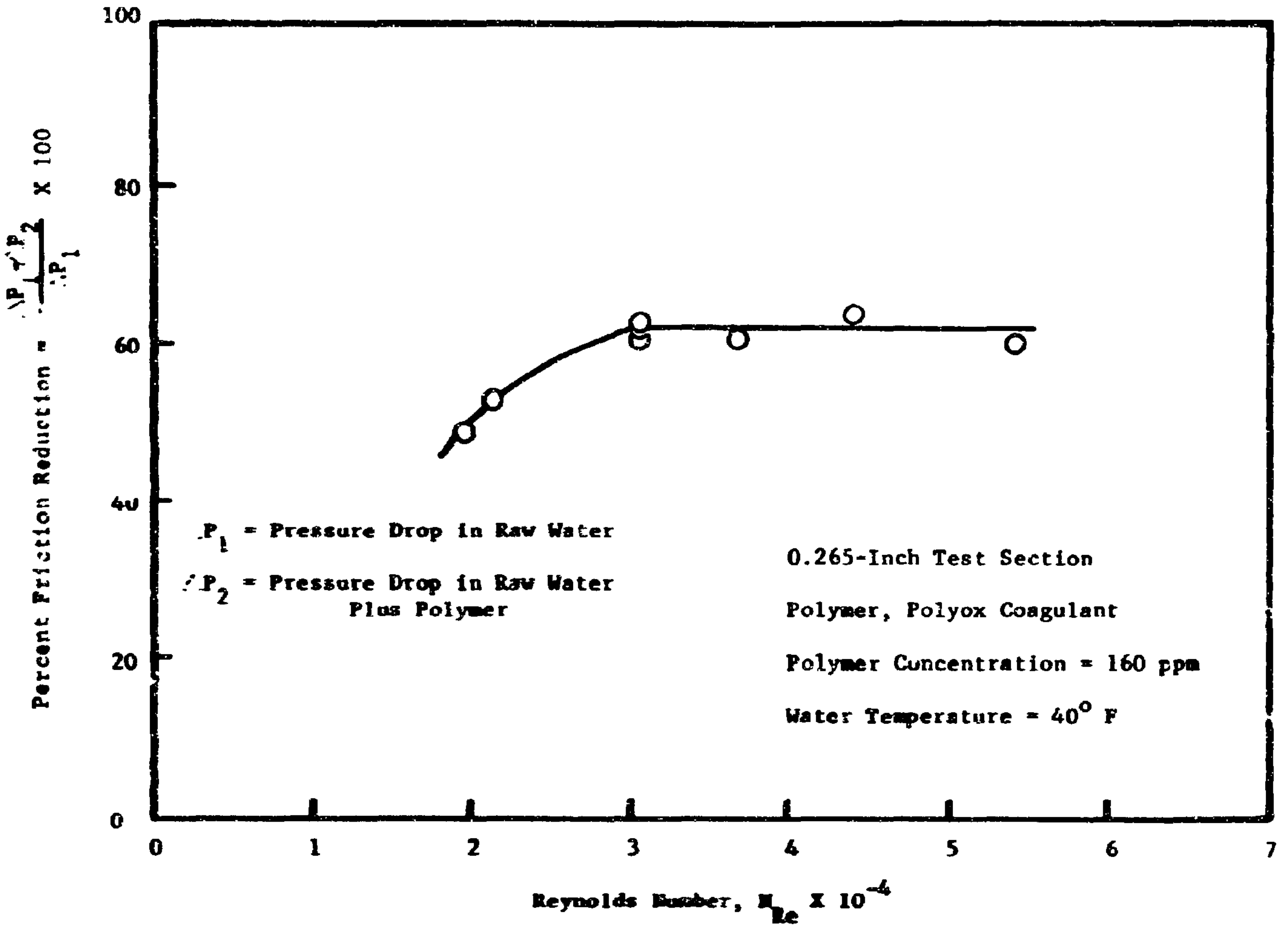

FIGURE 10. EFFECT OF REYNOLDS NUMBER ON FRICTION REDUCTION

The data are also plotted in Figure 11 in the form of Fanning Friction Factor as a function of Reynolds number. Shown for comparison is the curve for laminar theory, $16/N_{Re}$. The upper curves on the right side of the figure represent raw water data obtained in the North Star water tunnel and in the 10-inch facility at SAFHL. These curves are typical of those obtained with water flowing in pipes under turbulent conditions.

The lower curves were obtained by injecting the WSP slurries into the water-flow systems. The effect of Reynolds number on friction reduction is shown in the data obtained in the North Star facility. Flow in the 10-inch water pipe was apparently always greater than the "critical" Reynolds number -- the number below which friction-reducing agents are less effective.

The change in friction reduction from the 0.265-inch diameter pipe to the 10-inch diameter pipe was compared with data obtained by using Pruitt and Crawford 0.18-inch, 0.42-inch, and 1.6-inch pipes.[12] These data, along with the North Star data, are shown in Figure 12. The values for friction reduction plotted were those obtained using the optimum flow conditions, polymer levels, and polymer type. Note that there appears to be a logarithmic relationship between the friction reduction and the pipe diameter.

In another series of tests, the flow in the mixing section of the North Star facility was varied along with the flow in the test section. Reducing the Reynolds number of the mixing section produced results that did not differ appreciably from those obtained by reducing the velocity in the test section alone. Apparently the nozzles efficiently dispersed the polymer even when the Reynolds number of the mixing section was reduced to a value as low as 2500. When the flow in the mixing section of the North Star facility was reduced to Reynolds number of 2500, the flow in the test section was reduced to the region of poorer friction reduction shown in Figure 11.

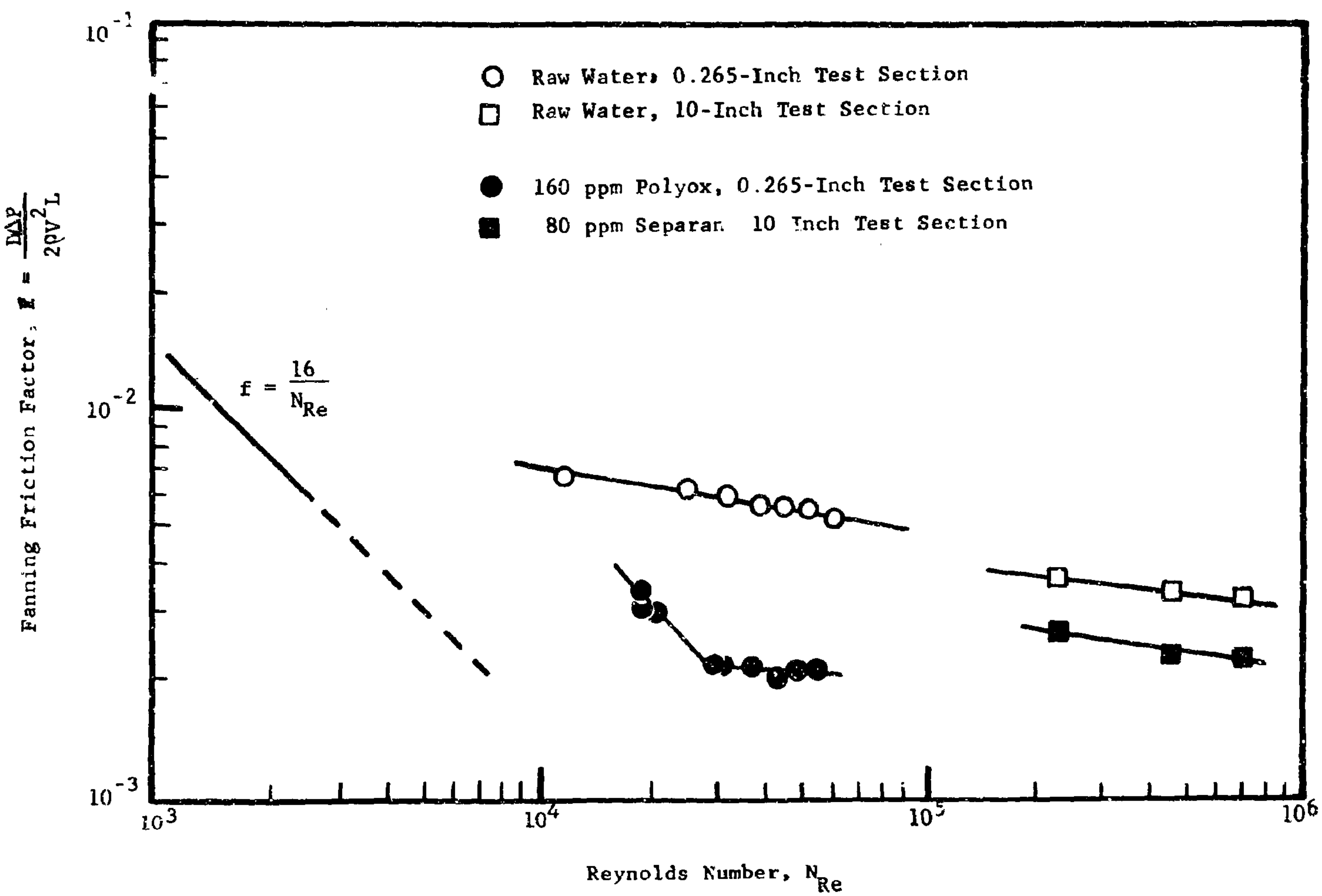

FIGURE 11. VARIATION OF FRICTION FACTOR WITH REYNOLDS NUMBER IN SMALL AND LARGE TEST SECTIONS

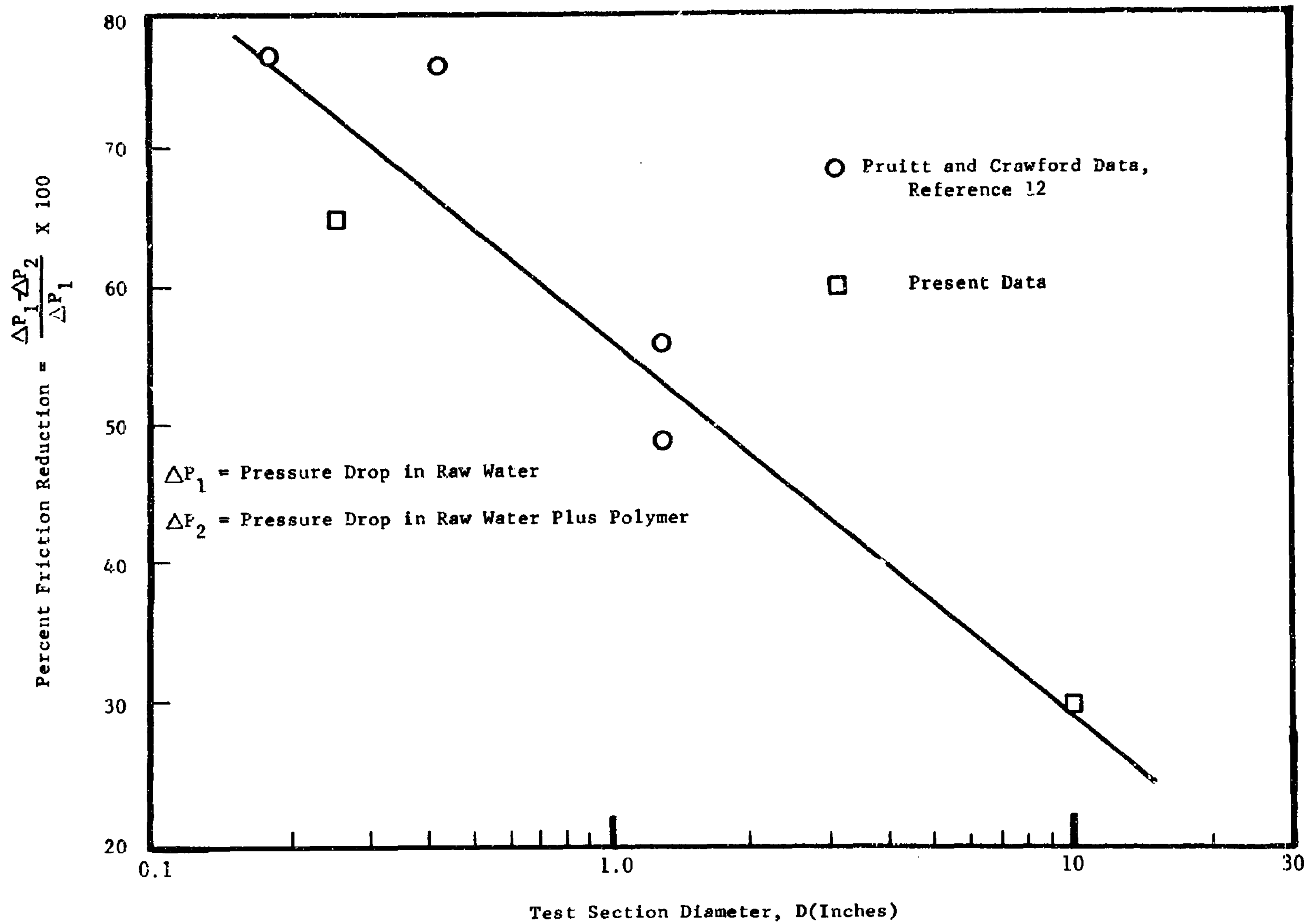

FIGURE 12. EFFECT OF TEST SECTION DIAMETER ON FRICTION REDUCTION

Injection of Concentrated Slurries

Two methods were used to test the injection of concentrated slurries into flowing water. In the first, high-solids slurries were injected into a two-inch Plexiglas pipe in which water was flowing at a Reynolds number of about 45,000. Figure 8 showed a 35-percent Separan in PPG slurry being injected into the water, where the flow patterns were made visible by the addition of a red dye to the slurry. The slurry dispersed well, and the slurry particles seemed to dissolve rapidly. It should be noted that the rate of slurry injection (990 grams per minute) was sufficient to give concentration of 3000 ppm, far higher than the 80 ppm necessary for optimum friction reduction.

The second method was the injection of 45-percent Separan AP30 slurry into the 10-inch diameter facility at SAFHL. The results of these tests are shown in Table 6 and Figure 11. They parallel the results obtained in the North Star facility, except the friction reduction was approximately half that found at North Star. There was also a difference in the friction reduction determined between two measuring stations, as noted in Table 6. The first measuring station started 94 feet downstream from the slurry injection point and continued for 46 feet; the second station started 140 feet from the slurry injection point and continued for 42 feet. The friction reduction was greater in the second half of the test section. It is doubtful that mixing time was the cause of the difference because the mixing times were always longer than the optimum time found in the North Star facility (Table 3). Thus, migration of the dissolved polymer to the pipe wall was not completed in the distance between the injection point and the first test section, a length of 113 pipe diameters.

TABLE 6

FRICTION REDUCTION IN TEN-INCH PIPE
USING HIGH SOLIDS-SLURRY

Polymer Concentration In Water	Mixing Time*	Water Flow Volume	Water Flow Velocity	N_{Re}	Percent Friction Reduction 1st 46 Feet Of Test Section	Percent Friction Reduction 2nd 42 Feet Of Test Section
ppm	Seconds	cfs	fps			
68	19	2.8	5	230,000	19	32
60	9.4	5.6	10	460,000	30	33
48	6.3	8.4	15	680,000	25	31

Water Temperature 34°F

Polymer Slurry was 45 Percent Separan AP30 in Polypropylene Glycol

*Distance Between Injection Point and First Manometer was 94 Feet

No noticeable increase in the flow rate was observed when the polymer was injected into the 10-inch diameter pipe. In the tests with the 0.26-inch ID pipe at North Star, the flow increased when polymer was injected. In the latter case, almost all the system pressure drop was in the test section, and the turbine pump output was sensitive to the head it pumped against. The head losses in the SAFHL flow system were mainly in the bends and valves before the injection point, and thus a change in flow was not noticed.

RECOMMENDATIONS FOR FURTHER RESEARCH

The effectiveness of the North Star polymer slurry injection system was demonstrated using the 10-inch diameter facility at SAFHL. This is apparently the largest pipe size ever used in investigations reporting the effects of the addition of friction-reducing polymers on friction in water-flow systems. Although the tests were not extensive, the positive results obtained were very encouraging. It should be noted that the injection system ran smoothly, and no evidence was found of fouling of the injection system by water.

Further work with the 10-inch diameter facility could probably advance greatly the knowledge of the mechanism of friction reduction, because sampling probes could easily be inserted in this large-diameter pipe, allowing precise measurements of the flow conditions. Methods of investigating friction-reduction phenomena could include the injection of the polymer at different points, the use of injection nozzles with wider spray angles, and the use of flow-measuring devices such as hot-film probes. In some of these cases, the injection of water solutions of polymers would probably be more useful than slurry injection but would not be a great problem because of the long mixing time available in the 10-inch pipe. Further work with slurries could be profitably done because of the ability to use high-solids slurries in the flows required for good injection and dispersion.

The relationship between pipe size and friction reduction could also be expanded at SAFHL. The addition of a 5-inch pipe would be simple, and a 20-inch facility could be modified for test work. The use of the high-solids slurry injection makes work with such pipes far more practical than a system requiring the injection of one- or two-percent solutions.

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APPENDIX

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Roy E. Larson

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13. ABSTRACT

Dispersions (slurries) of up to 45 weight percent water-soluble polymers in nonsolvent carriers were effective for reducing drag in turbulent flowing water streams. Separan or Polyox, in polypropylene glycol, gave about 20 percent friction reduction in mixing times less than 0.3 seconds, and reductions of over 60 percent in 1.5 seconds, in a 0.26-inch i.d. tube. In a 10-inch pipe, friction reductions of 30 percent were obtained. Decreasing the water temperature from $40^{o}F$ to $30^{o}F$, and adding 3.5 percent salt to the water had only minor effects on friction reduction. The optimum concentration of polymer in water stream was approximately 80 ppm. Dispersions of polymer have been held 18 months without settling or dissolving.

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